Penn State/US NRC Rod Bundle Test Facility and Reflood Heat Transfer Program (RBHT)

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Program Background

- RBHT Contract was initiated in November 1997 with the Nuclear Regulatory Commission Office of Research.

- Is a joint program between the College of Engineering and the Applied Research Laboratory (ARL).

- Principal Investigators

  Dr. L.E. Hochreiter

  Dr. F-B. Cheung

  Dr. T.F. Lin

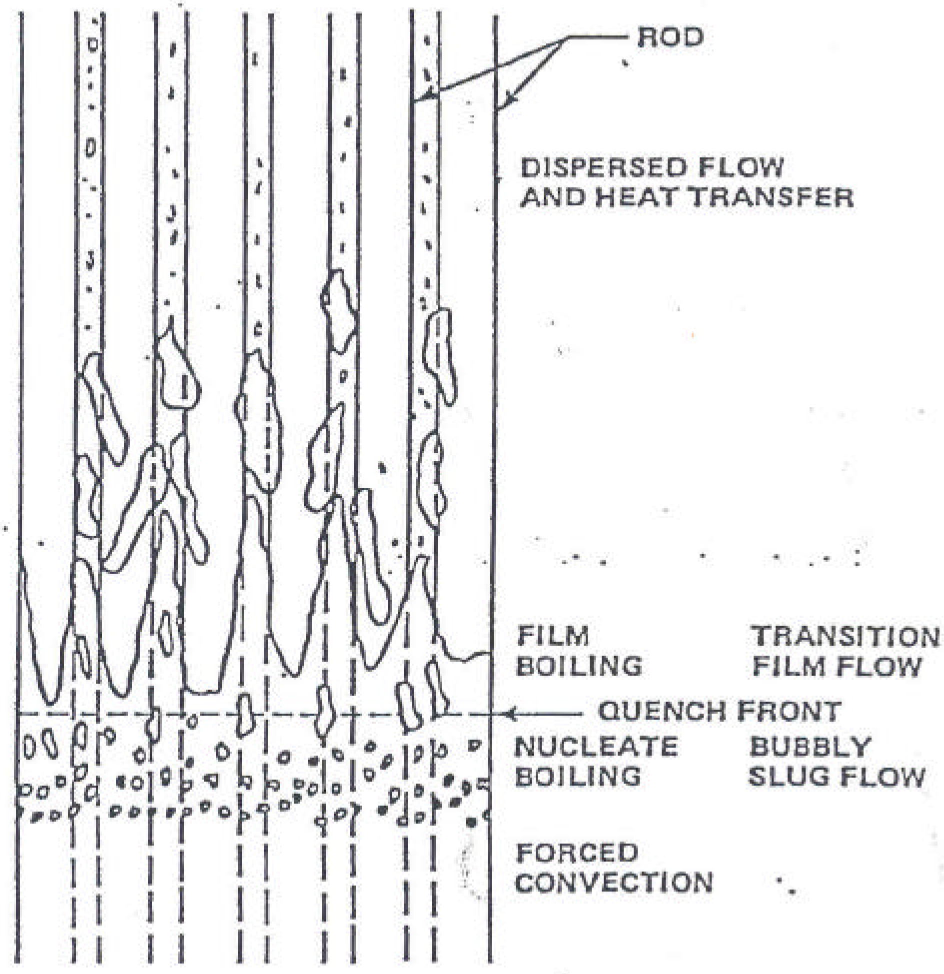
Background

- Loss of Coolant Accident (LOCA) is the most limiting design basis accident for PWRs.
- LOCA can limit the peak kW/ft values as well as the allowable power shapes for the plant operation.
- LOCA is a ‘calculated’ accident, the performance of the safety systems in mitigating the accident depends on the computer models used.

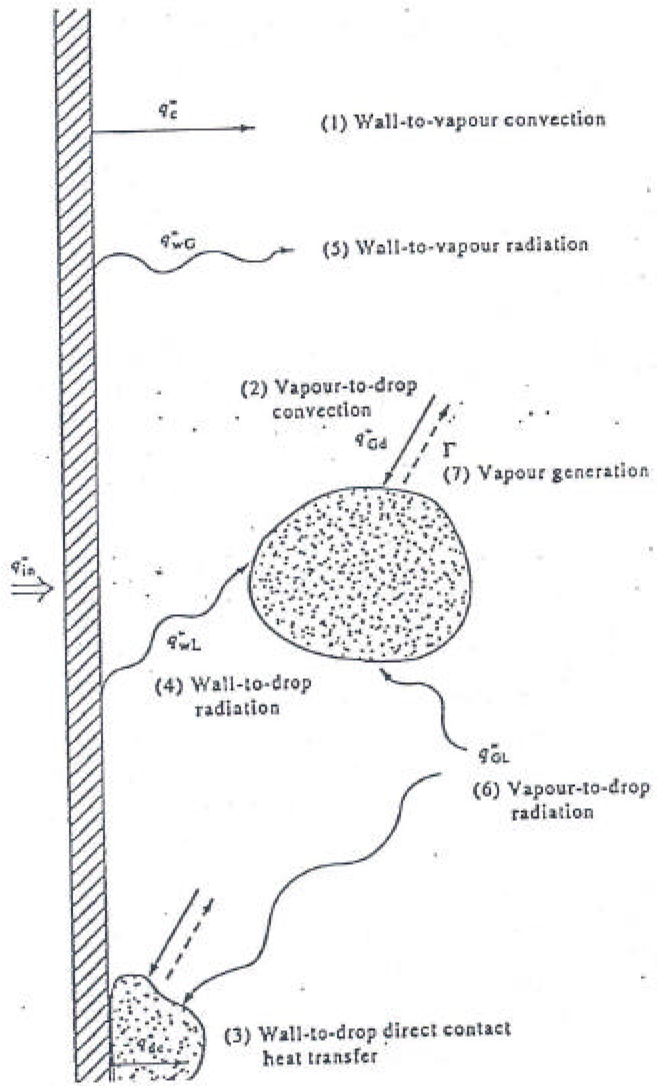
Peak Cladding Temperature (PCT) is calculated to occur during the Reflood period of the transient.

- Heat transfer rates are the smallest.
- Several different heat transfer mechanisms control the heat transfer.
- Flow is highly dispersed and non-equilibrium with superheated steam and liquid droplets.
- Quench front progresses up the fuel rods as the core quenches.
- Reflood is also the most limiting LOCA period with Best-Estimate codes.

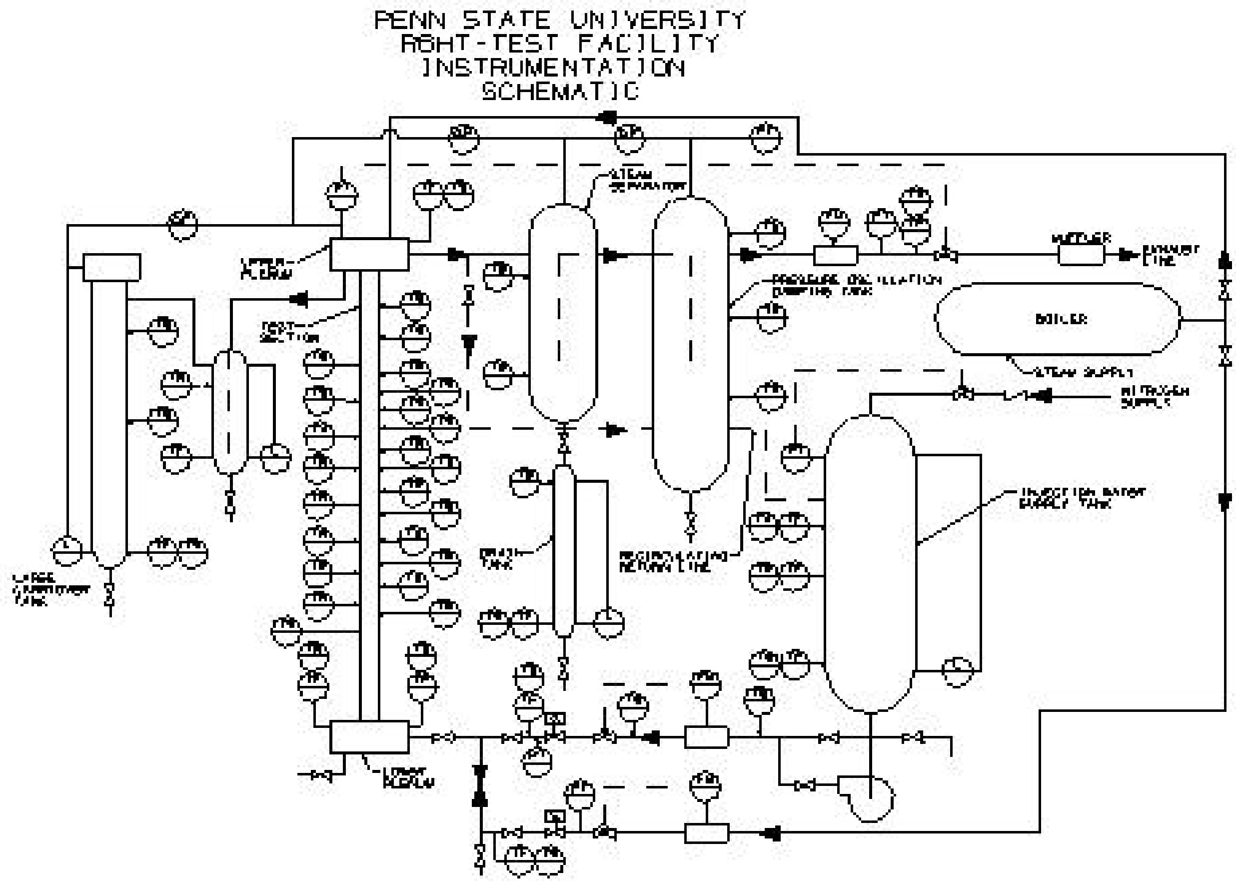
Flow Regimes During Reflood



Reflood Heat Transfer Phenomena



System Schematic with Instrumentation



RBHT

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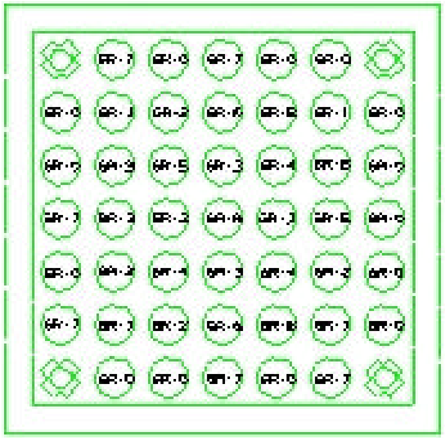
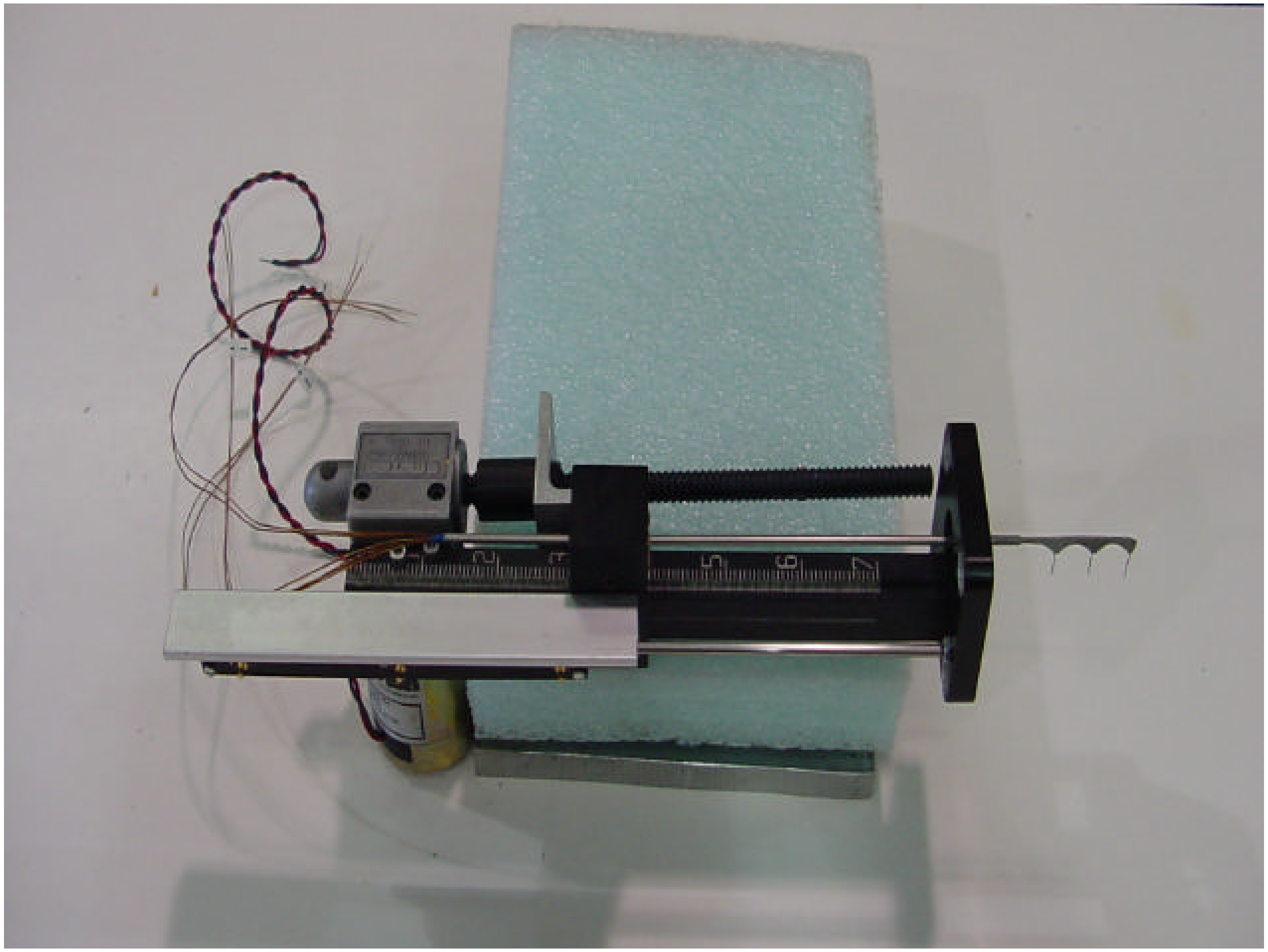
RBHT-TEST FACILITY
INSTRUMENTED HEATER ROD LOCATIONS

GROUP NO.	QUANTITY HEATER RODS
GR-0	14
GR-1	4
GR-2	4
GR-3	5
GR-4	3
GR-5	2
GR-6	3
GR-7	6
GR-8	4
TOTAL:	45

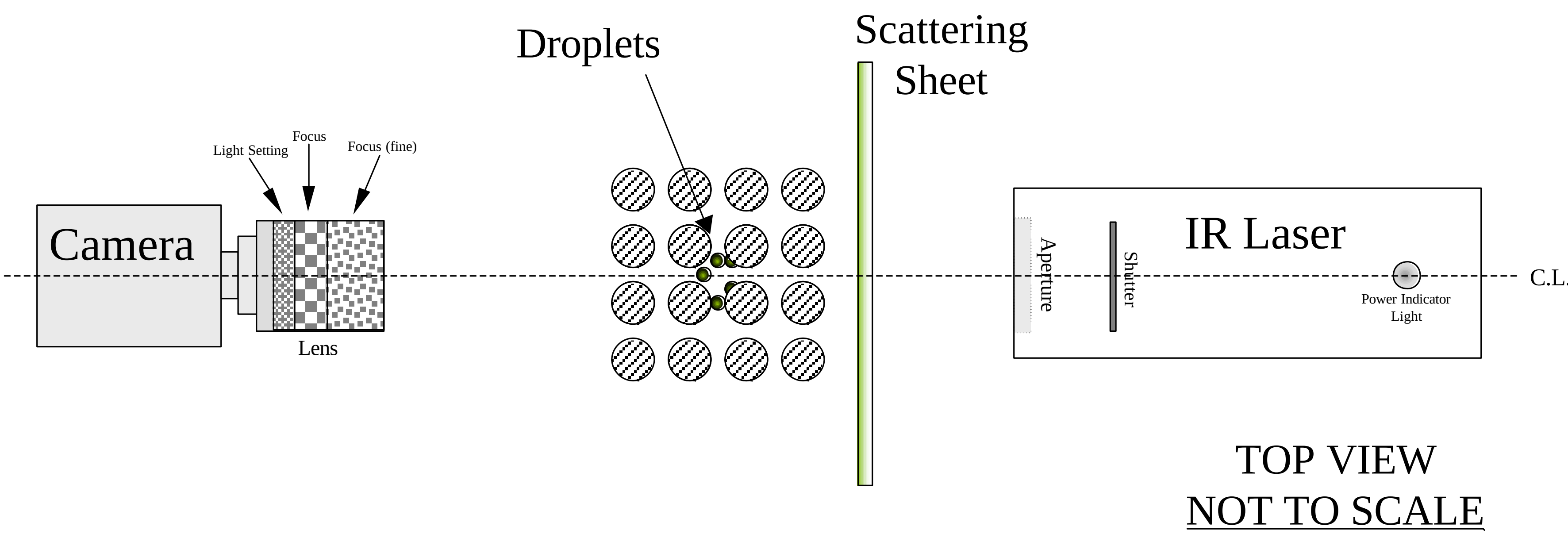


GR-0 UNINSTRUMENTED
GR-1 THRU 8 INSTRUMENTED

RBHT – Steam Probe Rake



Laser Illuminated Digital Imaging System Setup



RBHT

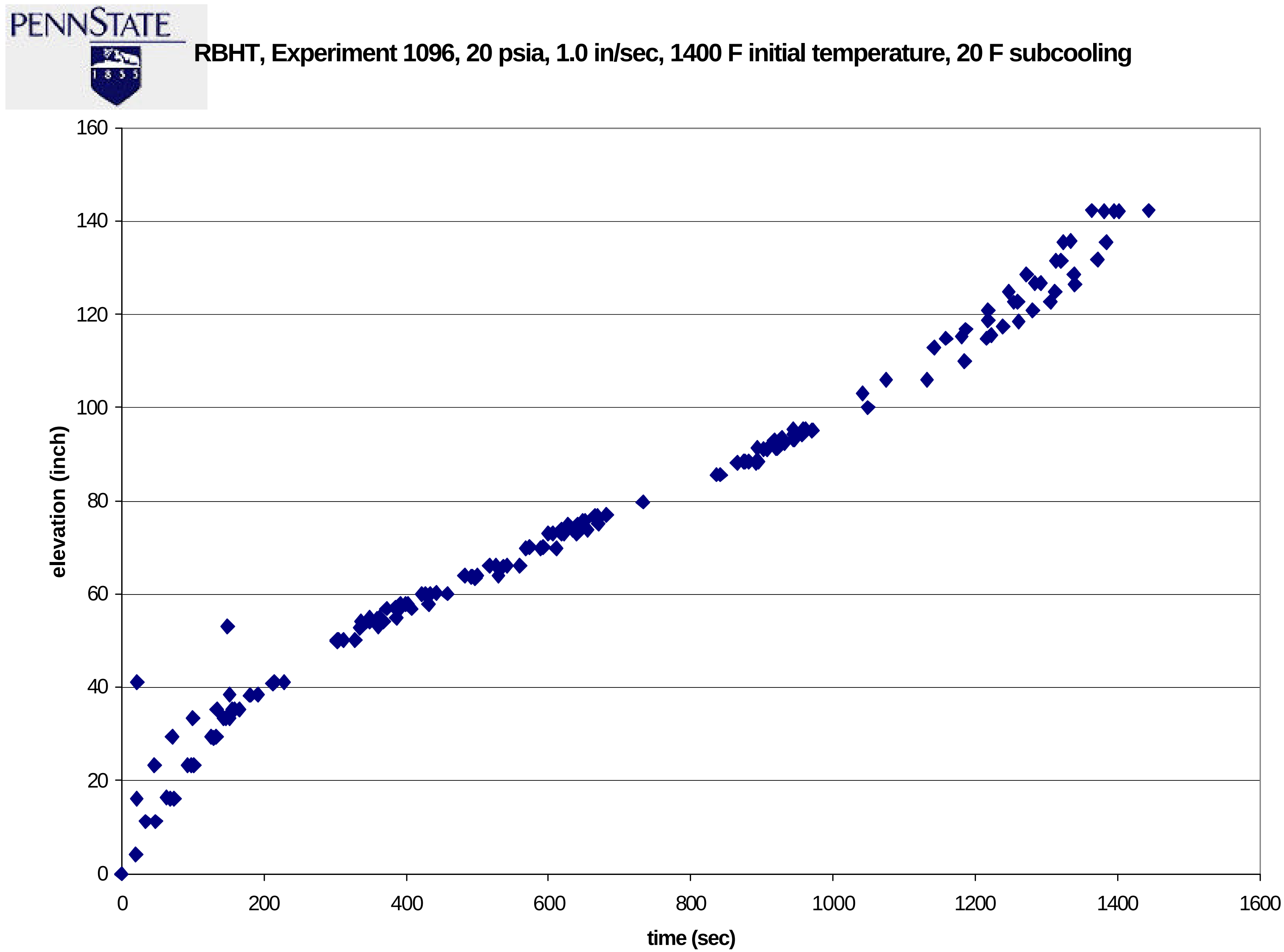
Flow Housing
Instrumentation

RBHT Matrix

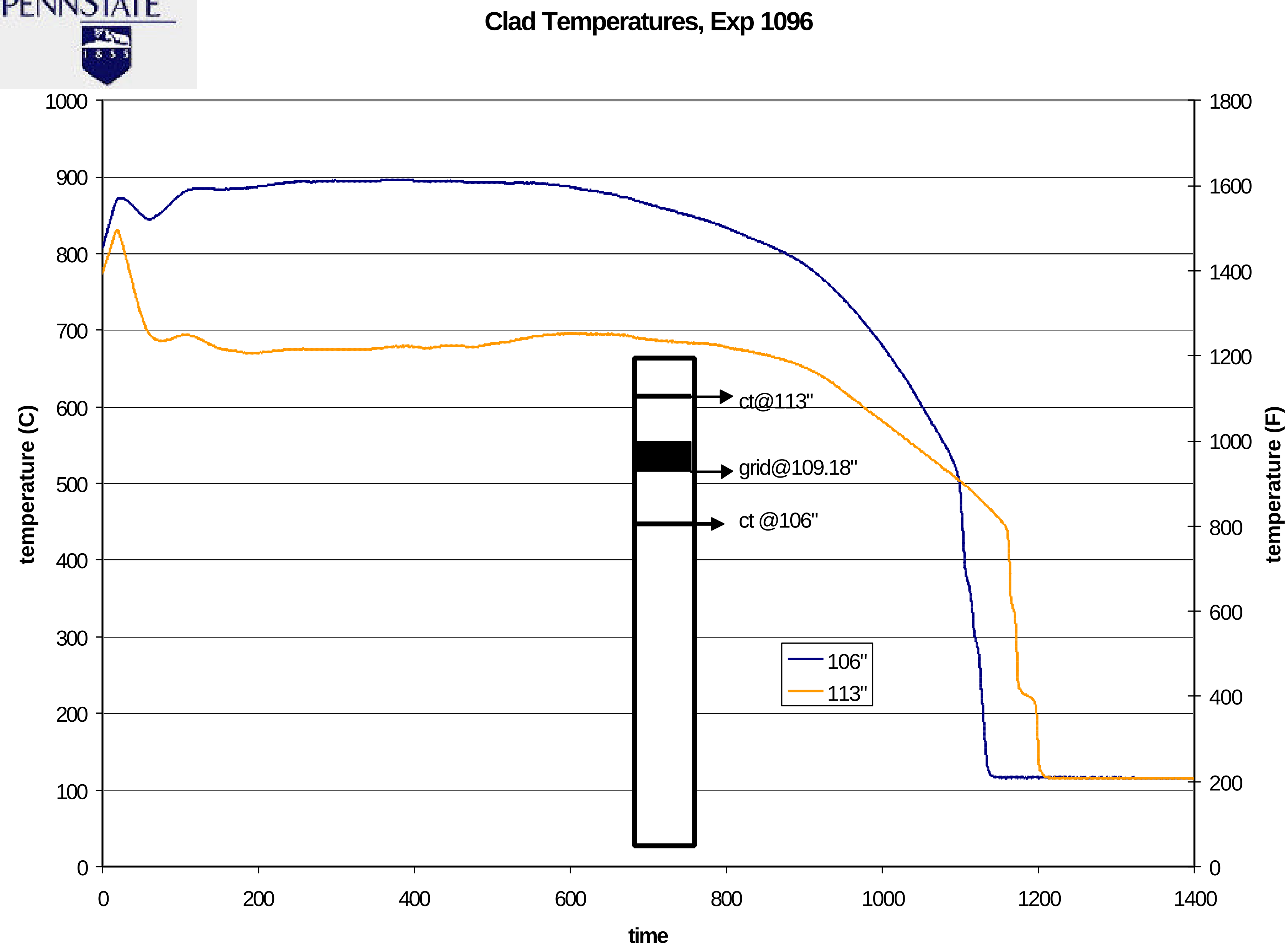
- Flooding Rate (inch/s): 0.54 - 10
- Pressure (psia): 20 - 60
- Inlet Subcooling (deg F): 20 - 150
- Initial Temperature (deg F): 1200 - 1700
- Peak Power* (kW/ft): 0.4 - 0.7

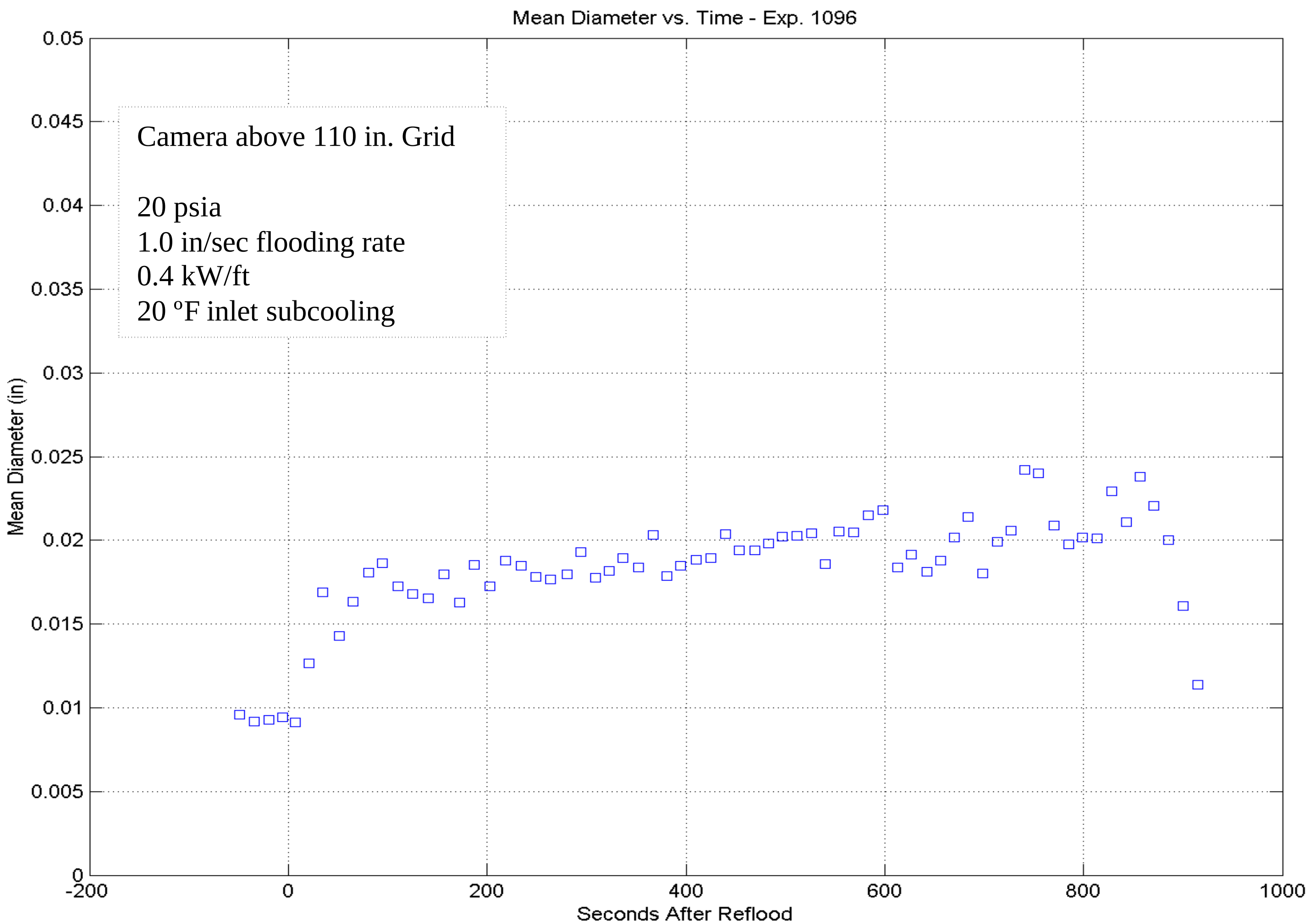
* *Power was held constant, did not decay.*

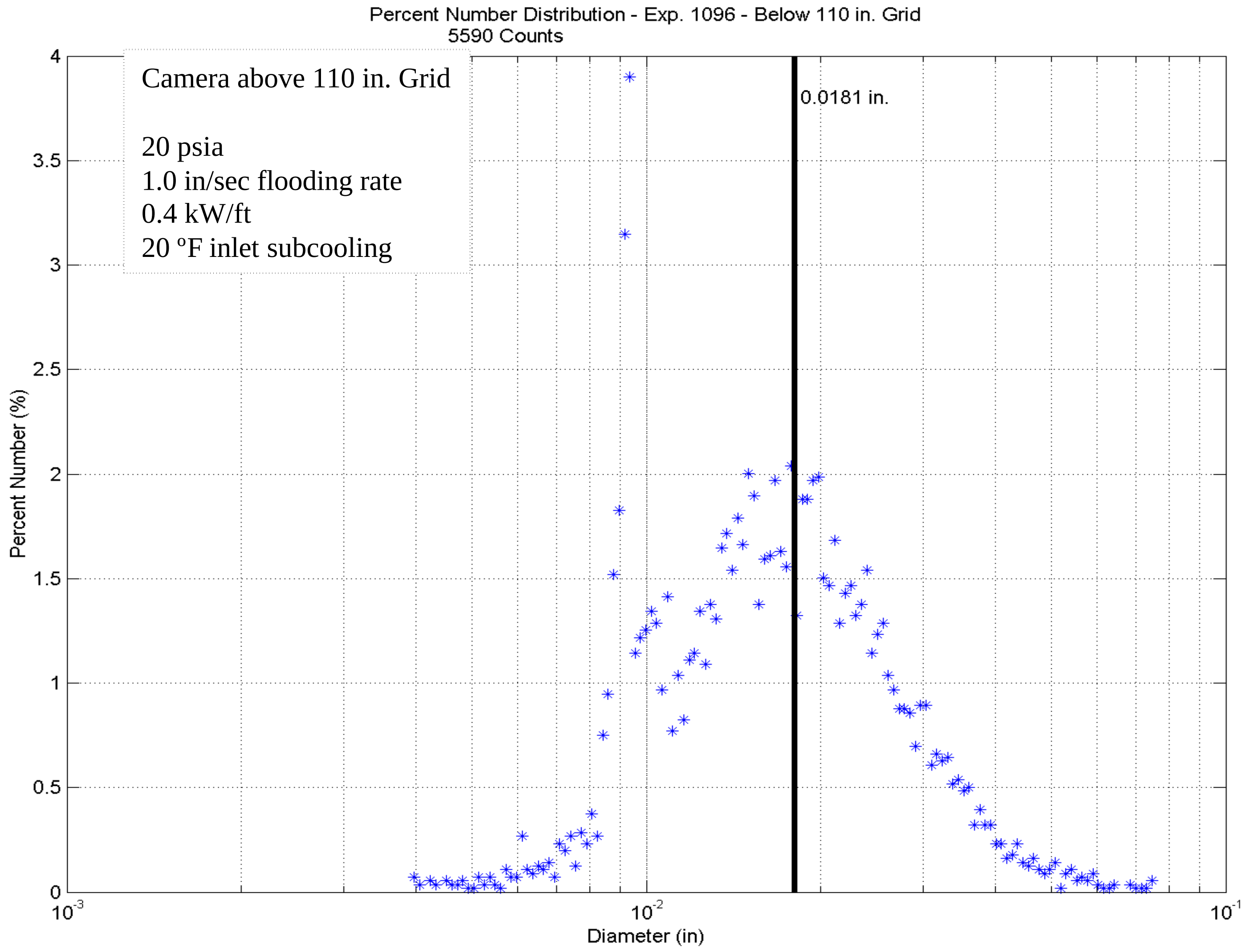
- Spacer grids can have a significant effect on the heat transfer due to
  - convective enhancement
  - grid quenching
  - entrained droplet break-up



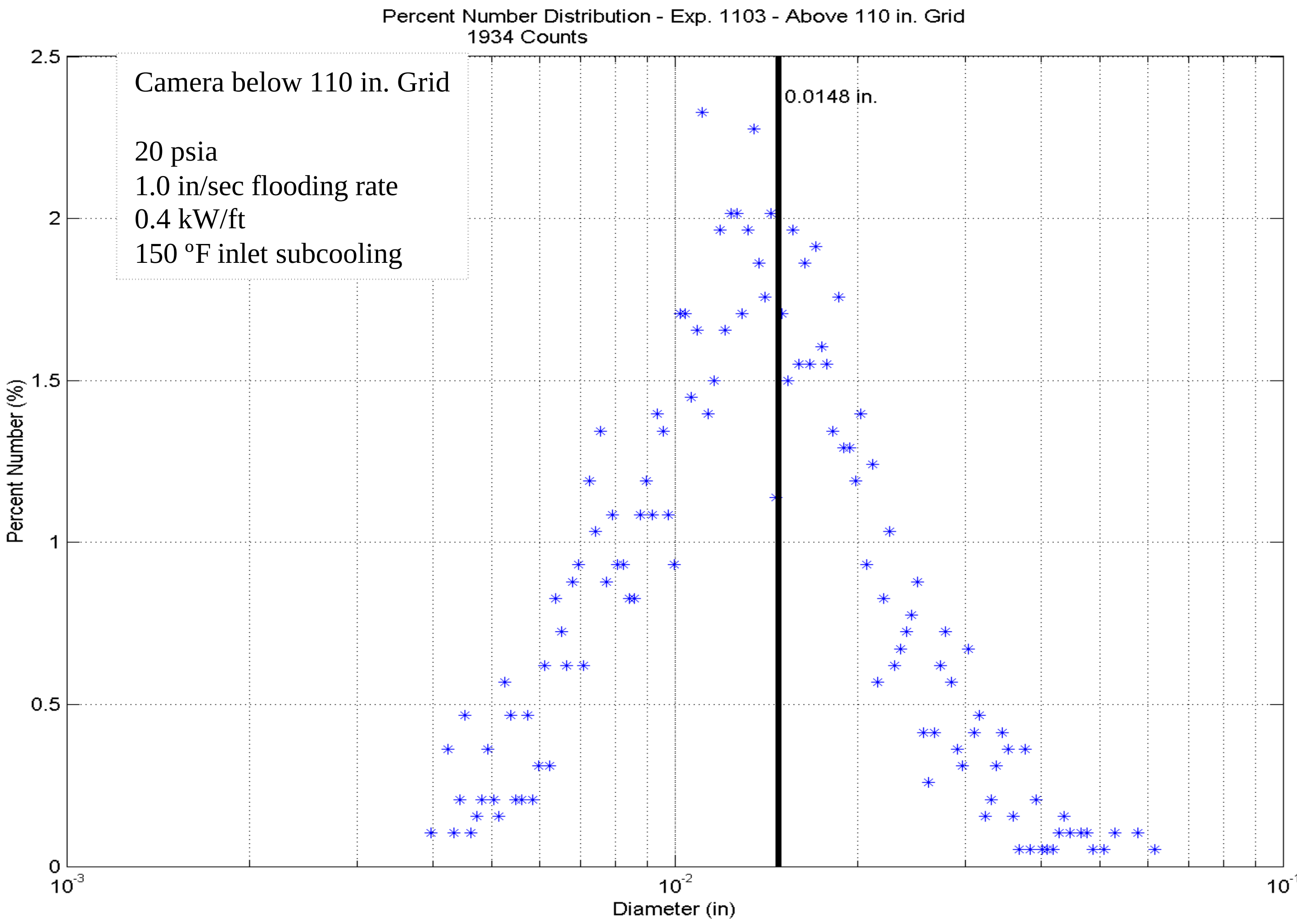
PENNSTATE
1 8 5 5
RBHT, Experiment 1096, 20 psia, 1.0 in/sec, 1400 F initial temperature, 20 F subcooling
elevation (inch)
time (sec)
0
20
40
60
80
100
120
140
160
0
200
400
600
800
1000
1200
1400
1600


Clad Temperatures, Exp 1096
temperature (C)
temperature (F)
time
ct@113"
grid@109.18"
ct @106"
106"
113"
0
100
200
300
400
500
600
700
800
900
1000
1200
1400
1600
1800

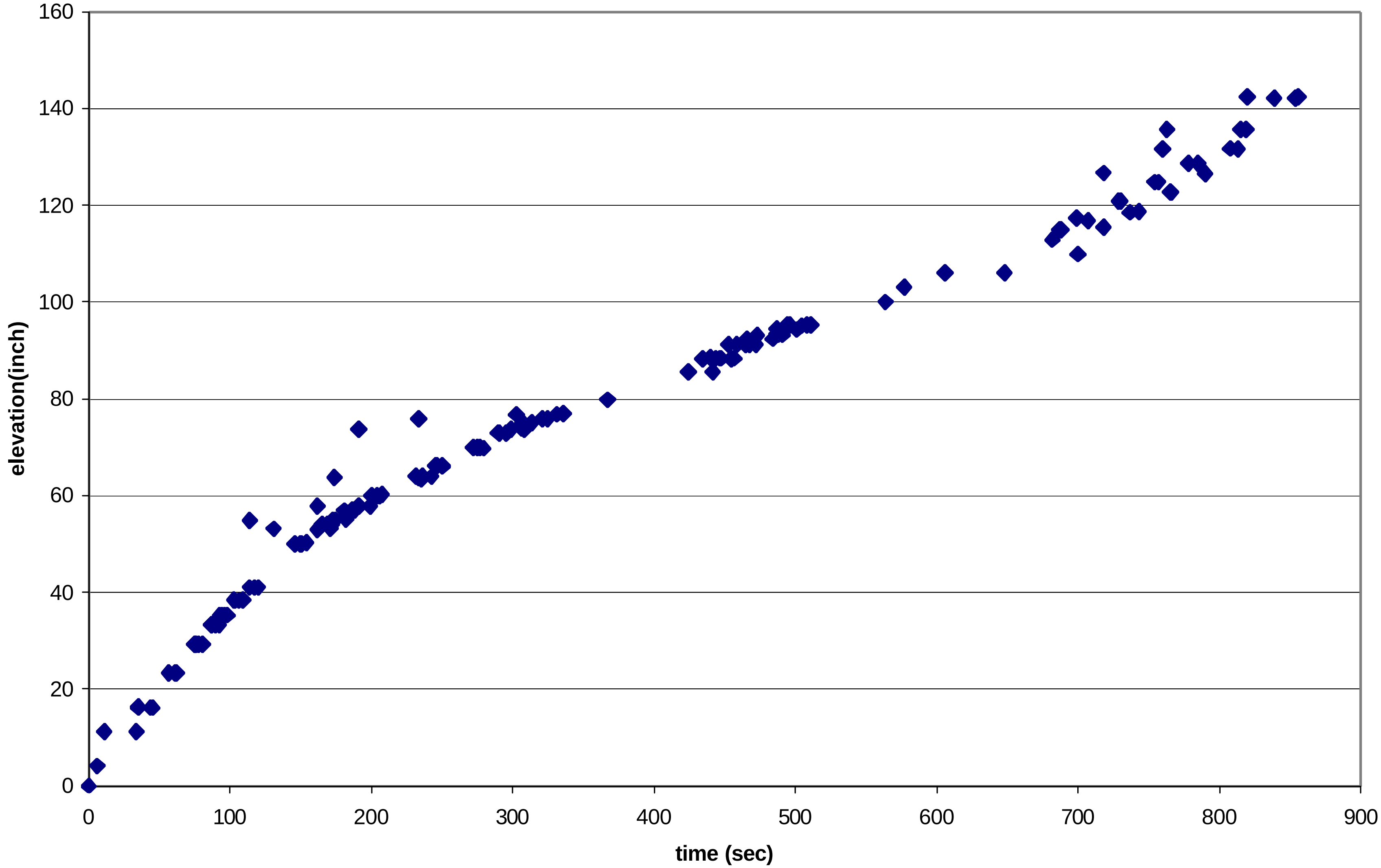

Mean Diameter vs. Time - Exp. 1096
Camera above 110 in. Grid
20 psia
1.0 in/sec flooding rate
0.4 kW/ft
20 °F inlet subcooling
Mean Diameter (in)
0.05
0.045
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
-200
0
200
400
600
800
1000
Seconds After Reflood

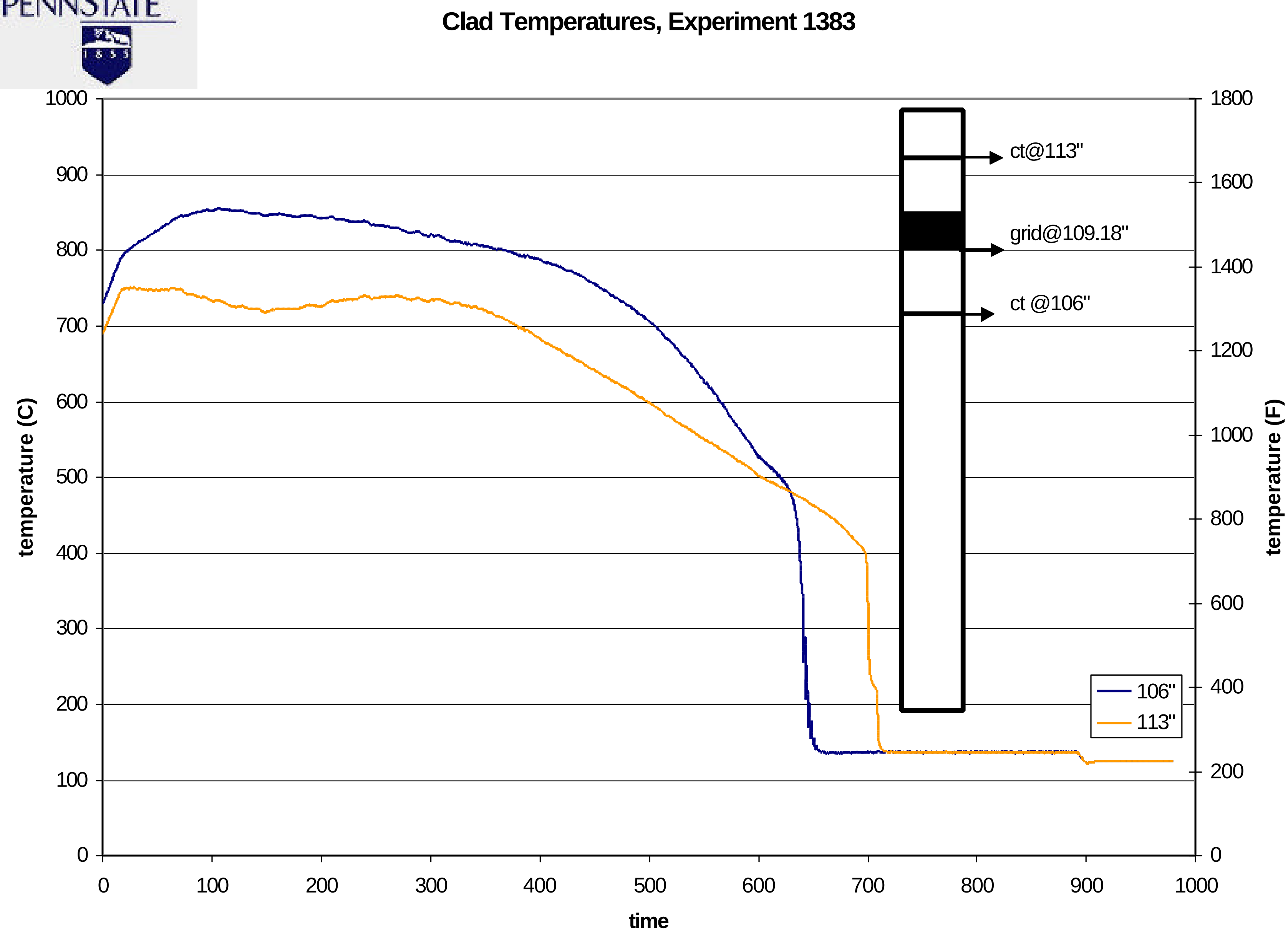


Percent Number Distribution - Exp. 1096 - Below 110 in. Grid
5590 Counts
Camera above 110 in. Grid
20 psia
1.0 in/sec flooding rate
0.4 kW/ft
20 °F inlet subcooling
0.0181 in.
Percent Number (%)
Diameter (in)

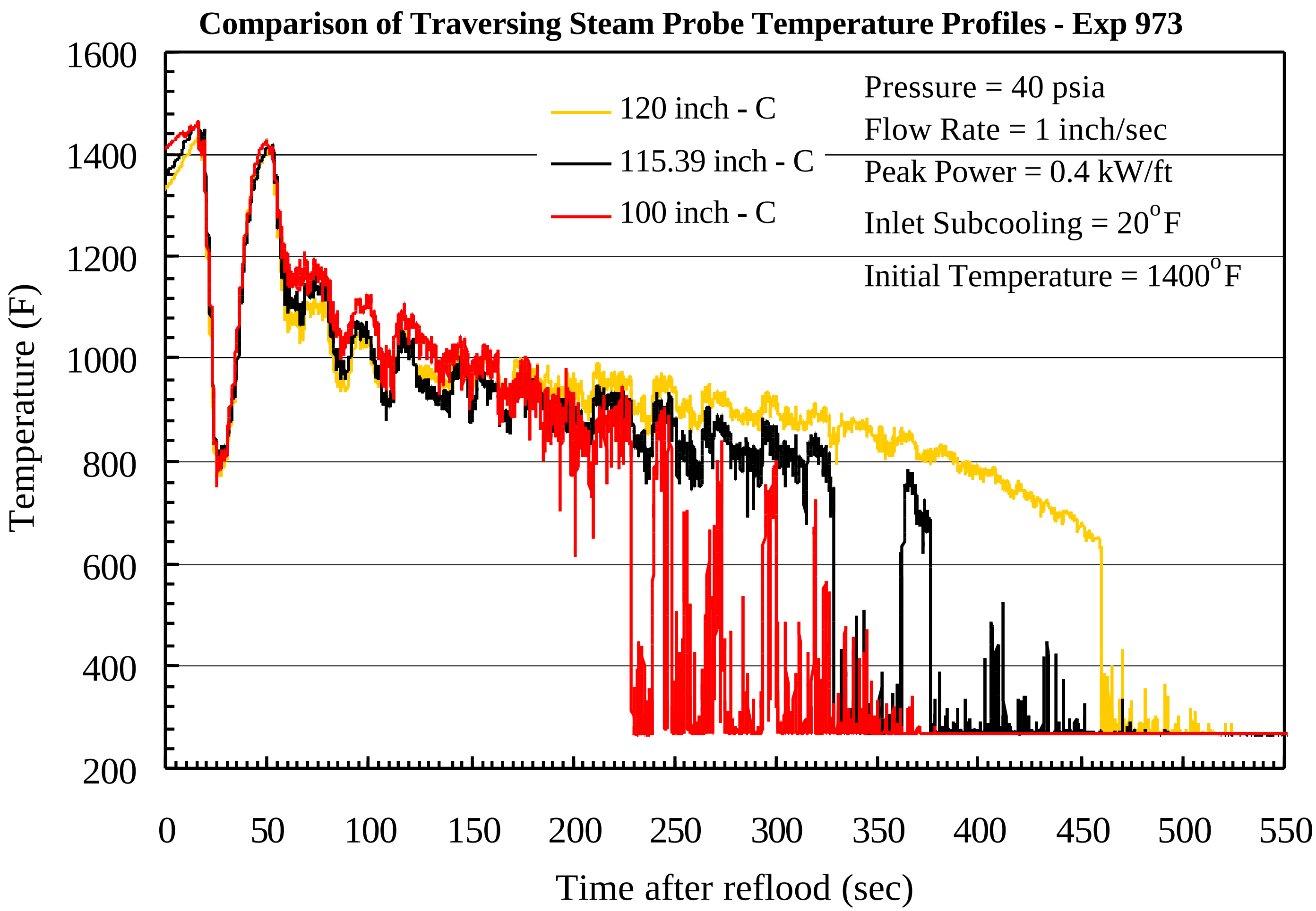

Percent Number Distribution - Exp. 1103 - Above 110 in. Grid
1934 Counts
Camera below 110 in. Grid
20 psia
1.0 in/sec flooding rate
0.4 kW/ft
150 °F inlet subcooling
0.0148 in.
Percent Number (%)
Diameter (in)
2.5
2
1.5
1
0.5
0
10-3
10-2
10-1

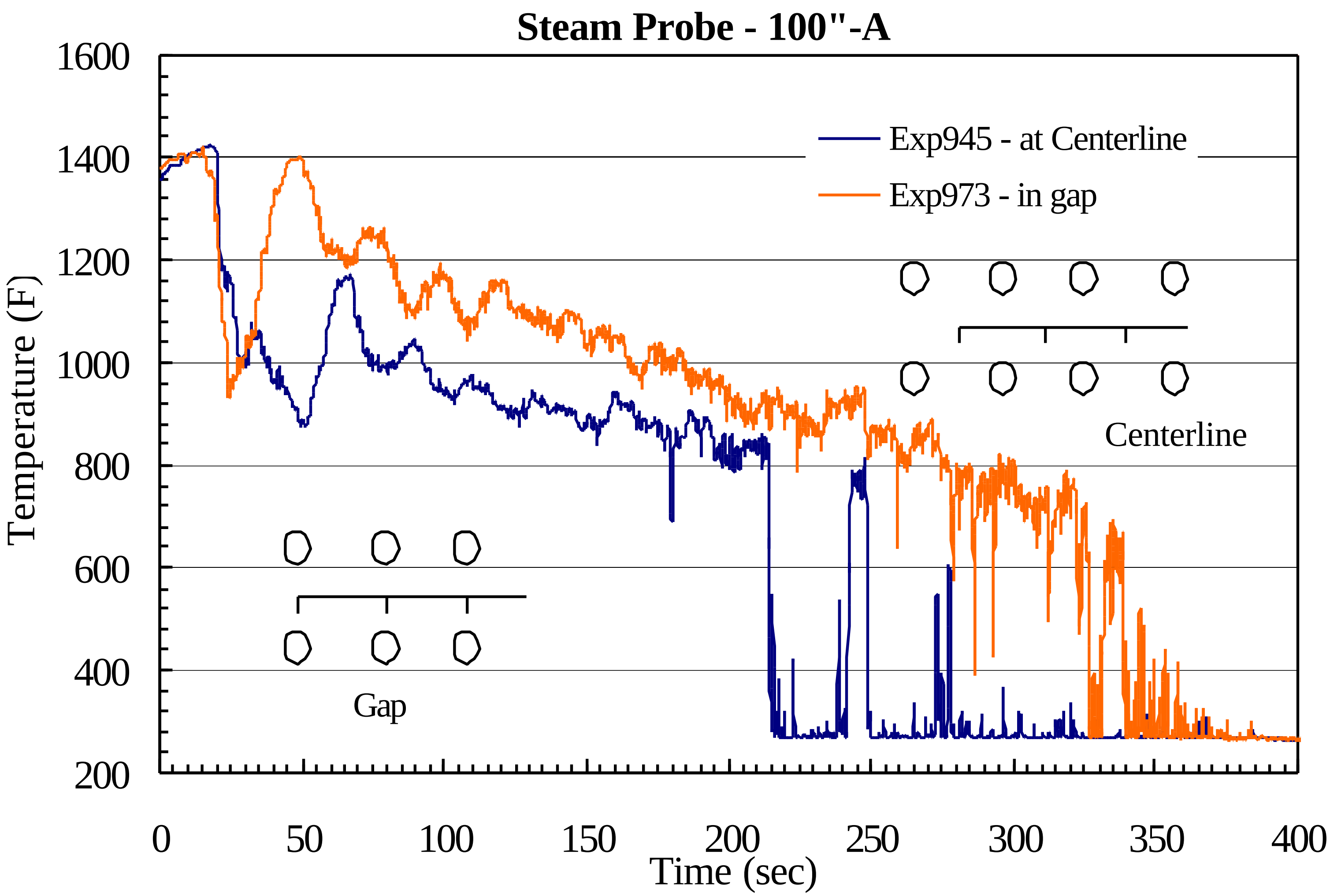
RBHT, Experiment 1383, 40 psia, 1.0 in/sec, 1400 F initial temperature, 20 F subcooling

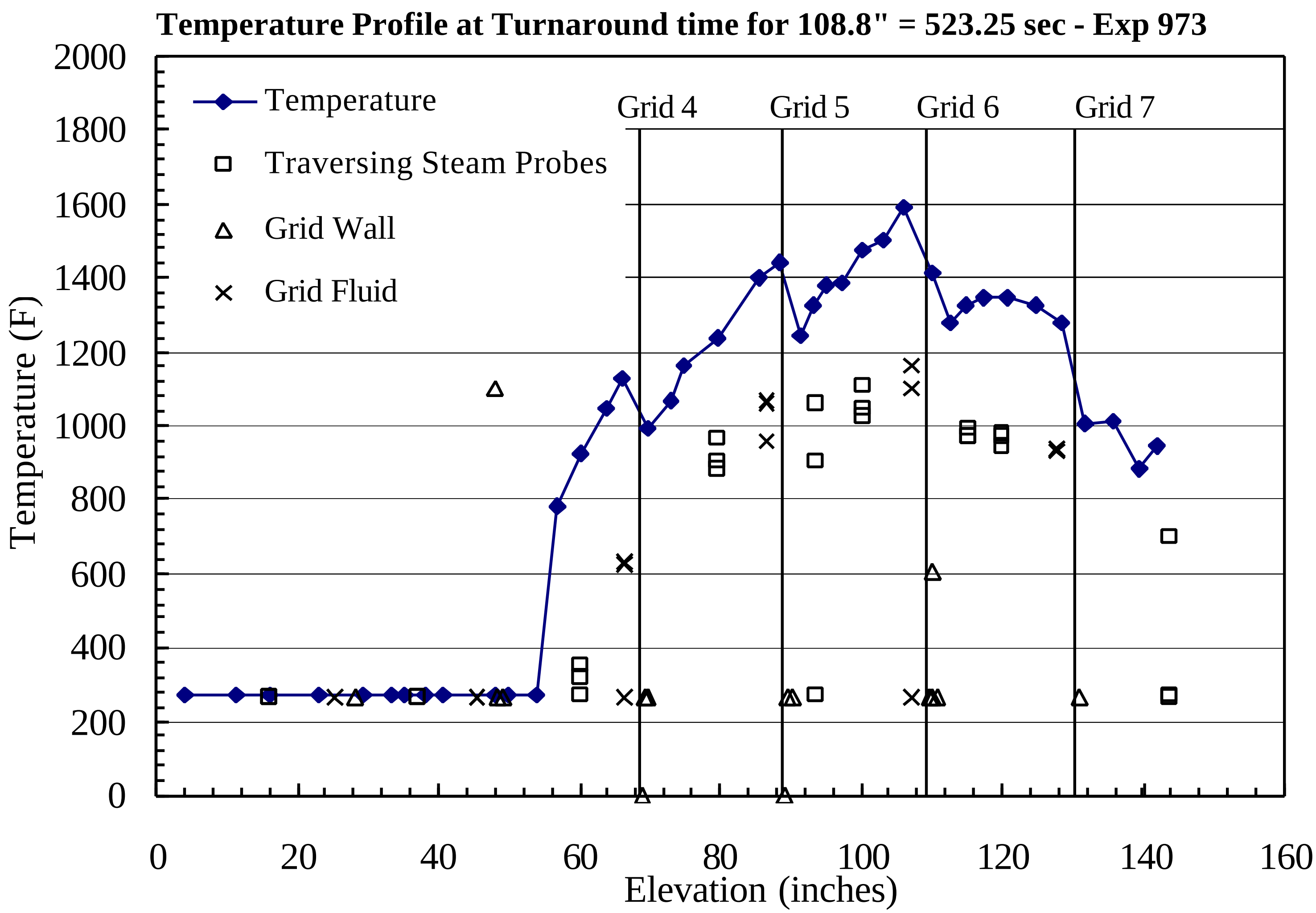




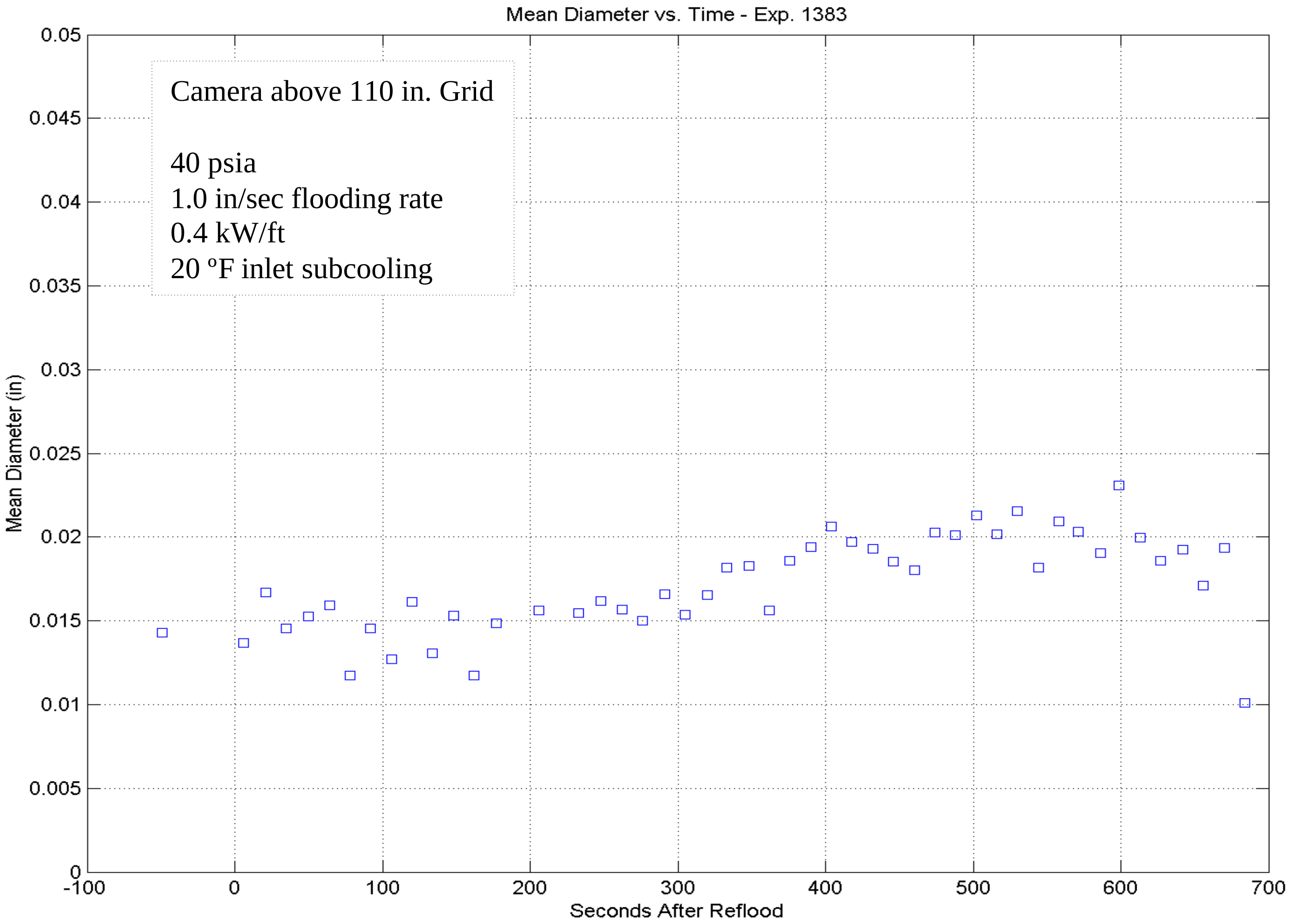
Clad Temperatures, Experiment 1383
temperature (C)
temperature (F)
time
0
100
200
300
400
500
600
700
800
900
1000
1200
1400
1600
1800
ct@113"
grid@109.18"
ct @106"
106"
113"


Comparison of Traversing Steam Probe Temperature Profiles - Exp 973
120 inch - C
115.39 inch - C
100 inch - C
Pressure = 40 psia
Flow Rate = 1 inch/sec
Peak Power = 0.4 kW/ft
Inlet Subcooling = 20°F
Initial Temperature = 1400°F
Temperature (F)
1600
1400
1200
1000
800
600
400
200
0
50
100
150
200
250
300
350
400
450
500
550
Time after reflood (sec)

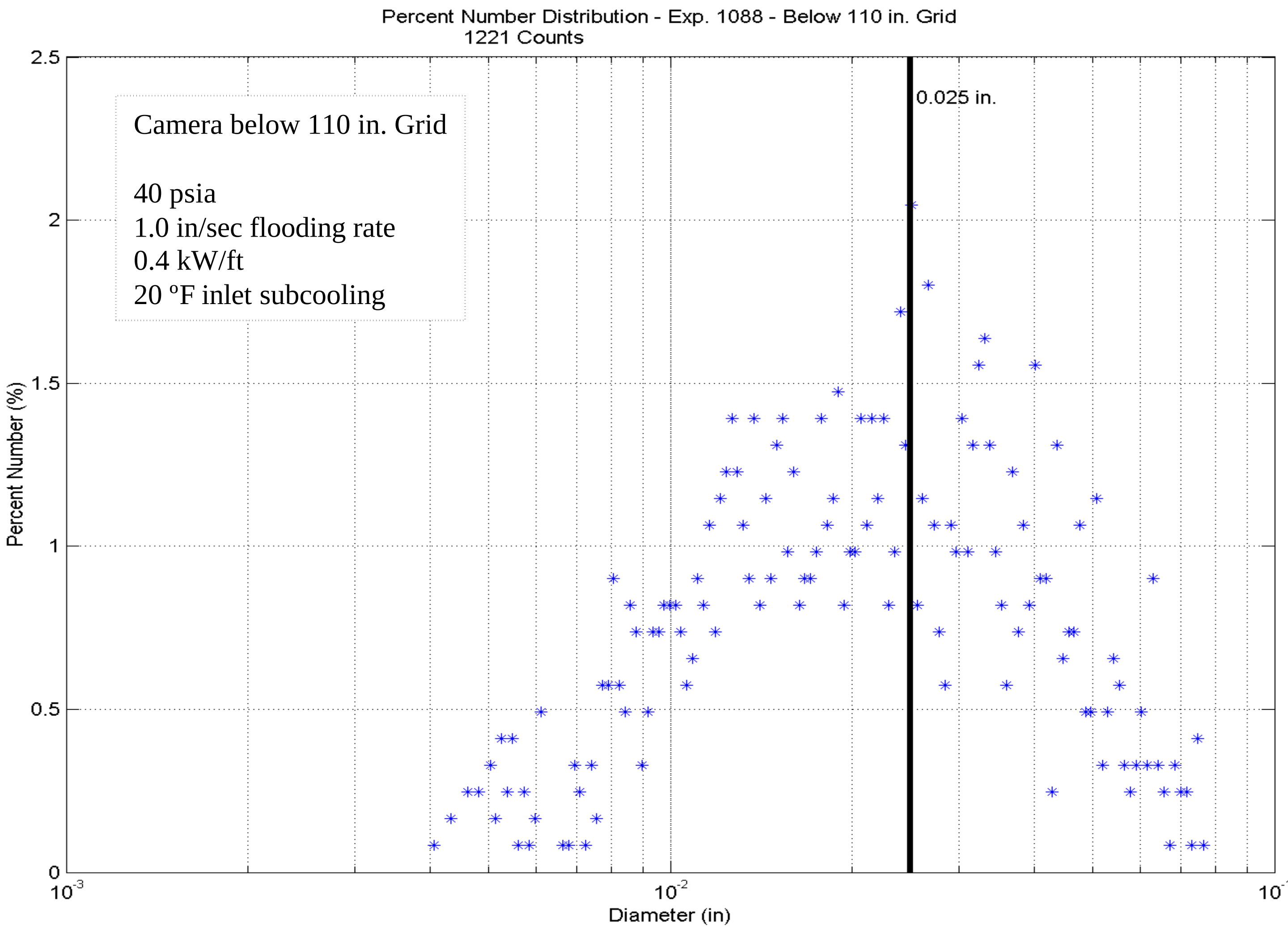

Steam Probe - 100"-A
Temperature (F)
Time (sec)
Exp945 - at Centerline
Exp973 - in gap
Gap
Centerline
1600
1400
1200
1000
800
600
400
200
0
50
100
150
200
250
300
350
400

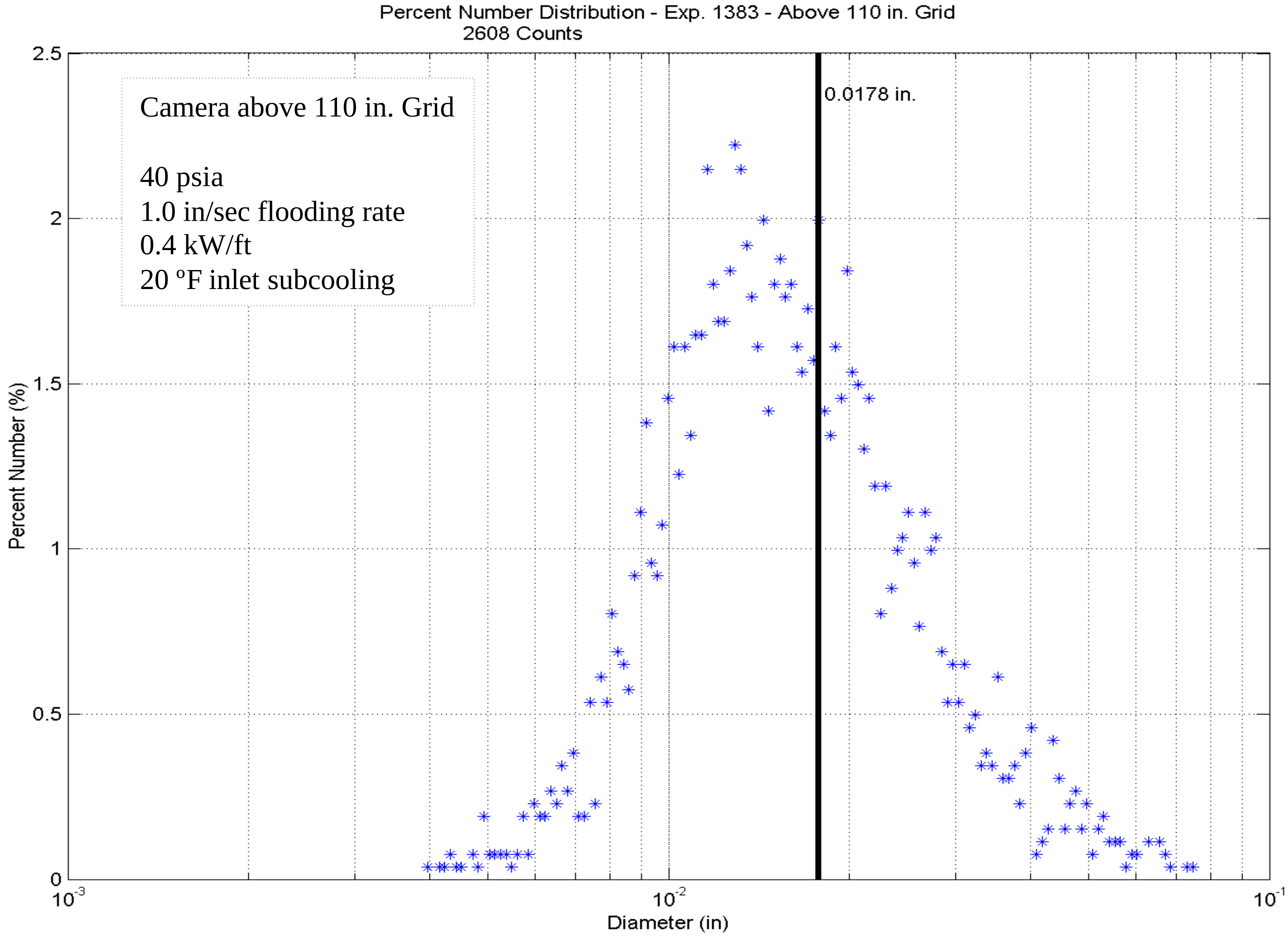


Temperature Profile at Turnaround time for 108.8" = 523.25 sec - Exp 973
Temperature
Traversing Steam Probes
Grid Wall
Grid Fluid
Grid 4
Grid 5
Grid 6
Grid 7
Temperature (F)
Elevation (inches)
2000
1800
1600
1400
1200
1000
800
600
400
200
0
0
20
40
60
80
100
120
140
160



Mean Diameter vs. Time - Exp. 1383
Camera above 110 in. Grid
40 psia
1.0 in/sec flooding rate
0.4 kW/ft
20 °F inlet subcooling
Mean Diameter (in)
0.05
0.045
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
-100
0
100
200
300
400
500
600
700
Seconds After Reflood

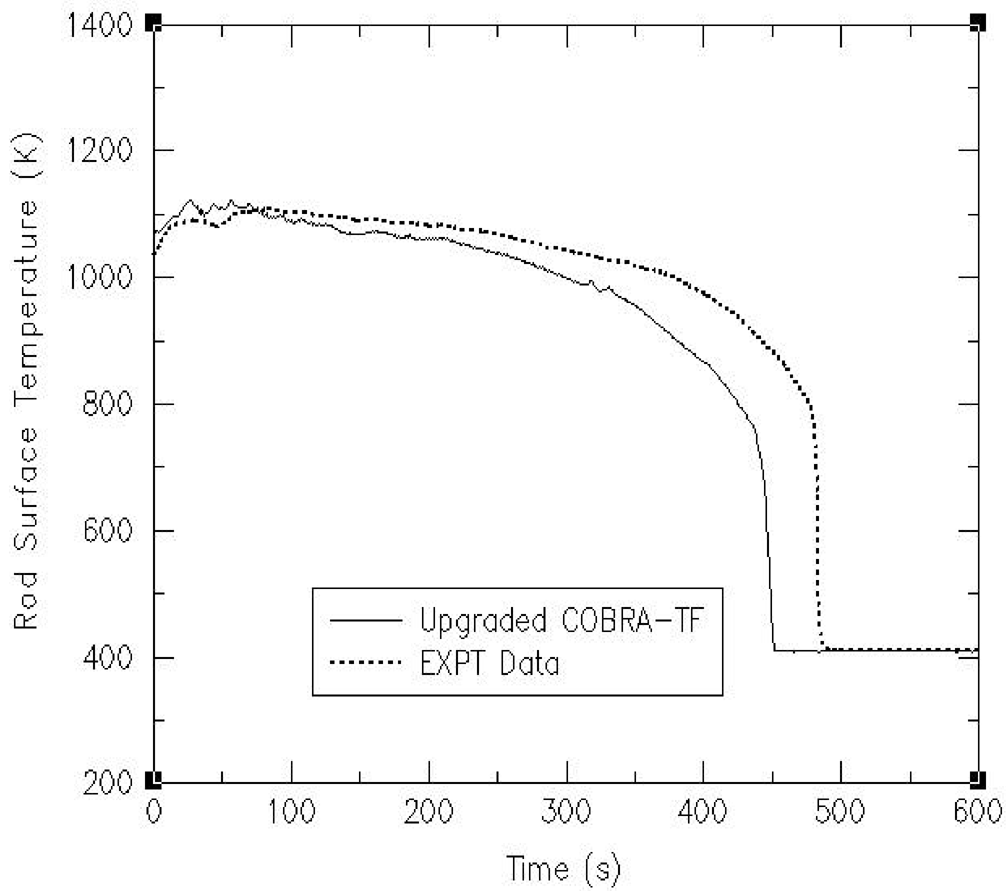

Percent Number Distribution - Exp. 1088 - Below 110 in. Grid
1221 Counts
Camera below 110 in. Grid
40 psia
1.0 in/sec flooding rate
0.4 kW/ft
20 °F inlet subcooling
0.025 in.
Percent Number (%)
Diameter (in)
0
0.5
1
1.5
2
2.5
10^{-3}
10^{-2}
10^{-1}


Percent Number Distribution - Exp. 1383 - Above 110 in. Grid
2608 Counts
Camera above 110 in. Grid
40 psia
1.0 in/sec flooding rate
0.4 kW/ft
20 °F inlet subcooling
0.0178 in.
Percent Number (%)
Diameter (in)
2.5
2
1.5
1
0.5
0
10-3
10-2
10-1

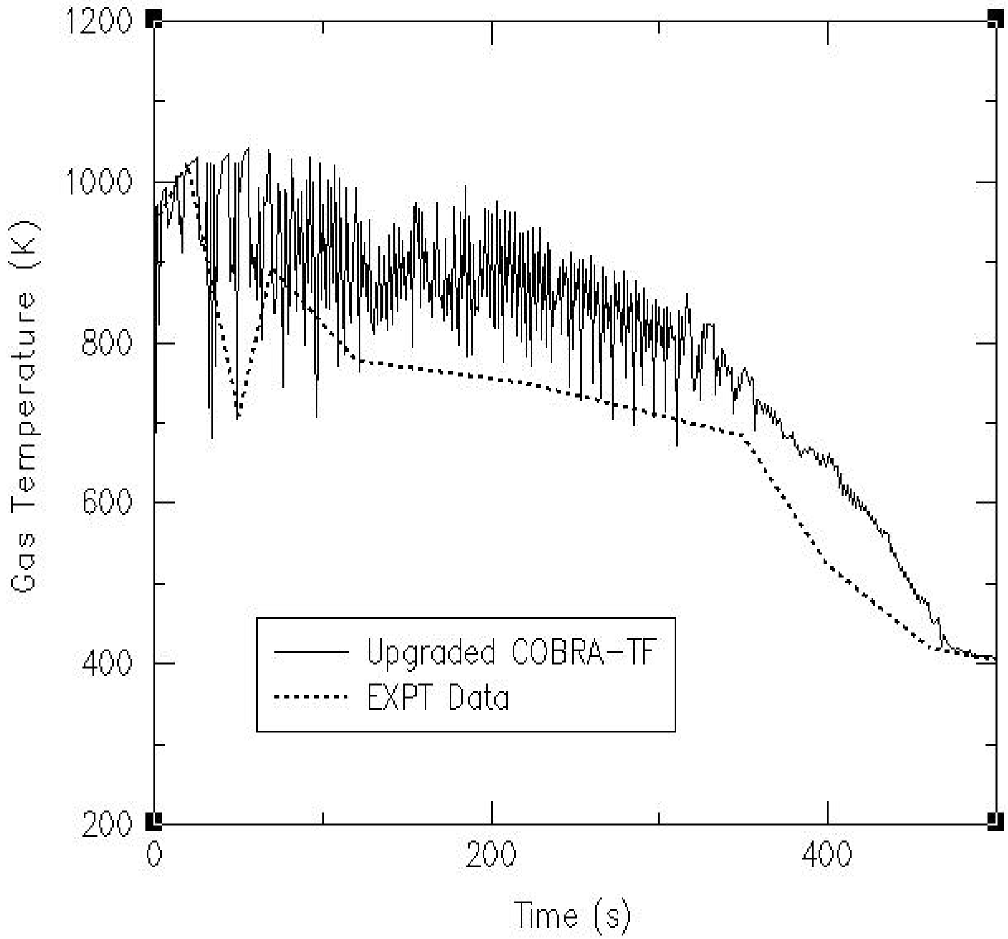
RBHT RUN 945

Upper Plenum Pressure	0.27 MPa
Initial Clad Temperature at 2.74m	1040 K
Rod Peak Power	1.3 kW/m
Cold Fill Rate	25.3 mm/sec
Injected Coolant Temperature	392K

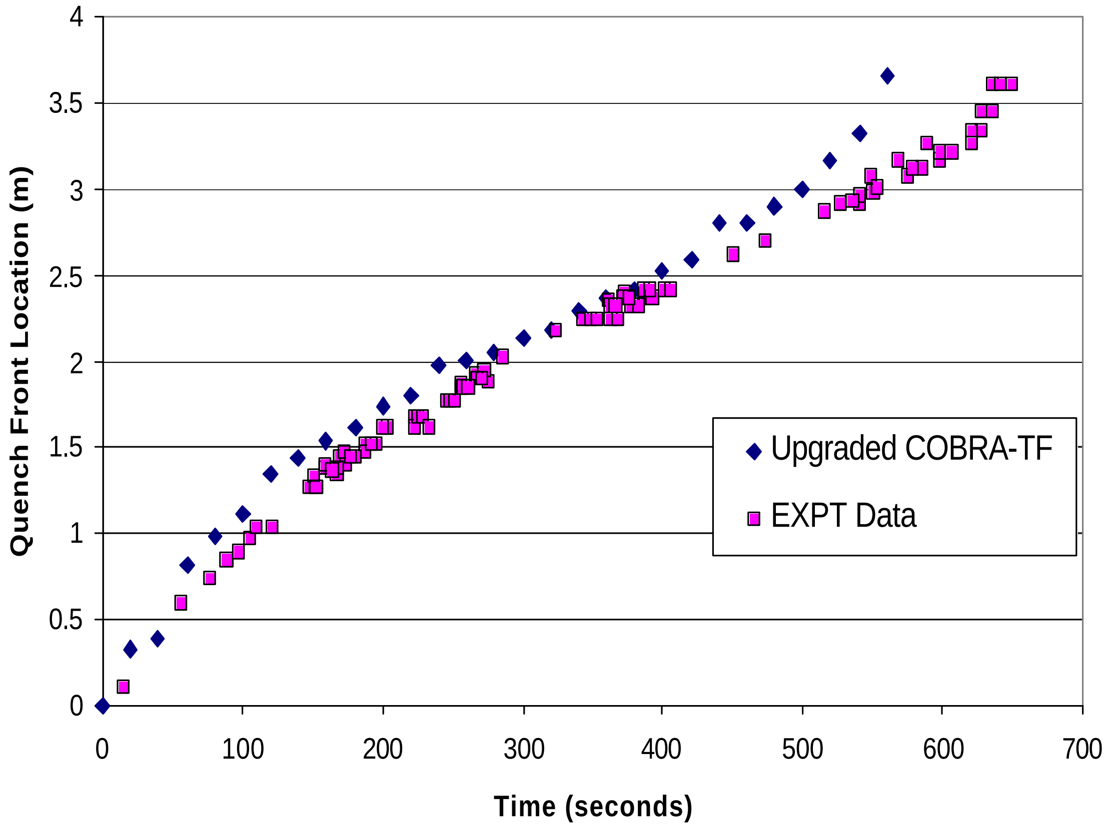
Comparison of Upgraded Code-Calculated and Experimentally Measured Clad Temperatures for RBHT – Run 945 at 2.74m Axial Elevation



Comparison of Upgraded Code-Calculated and Experimentally Measured Vapor Temperatures for RBHT – Run 945 at 2.92m Axial Elevation



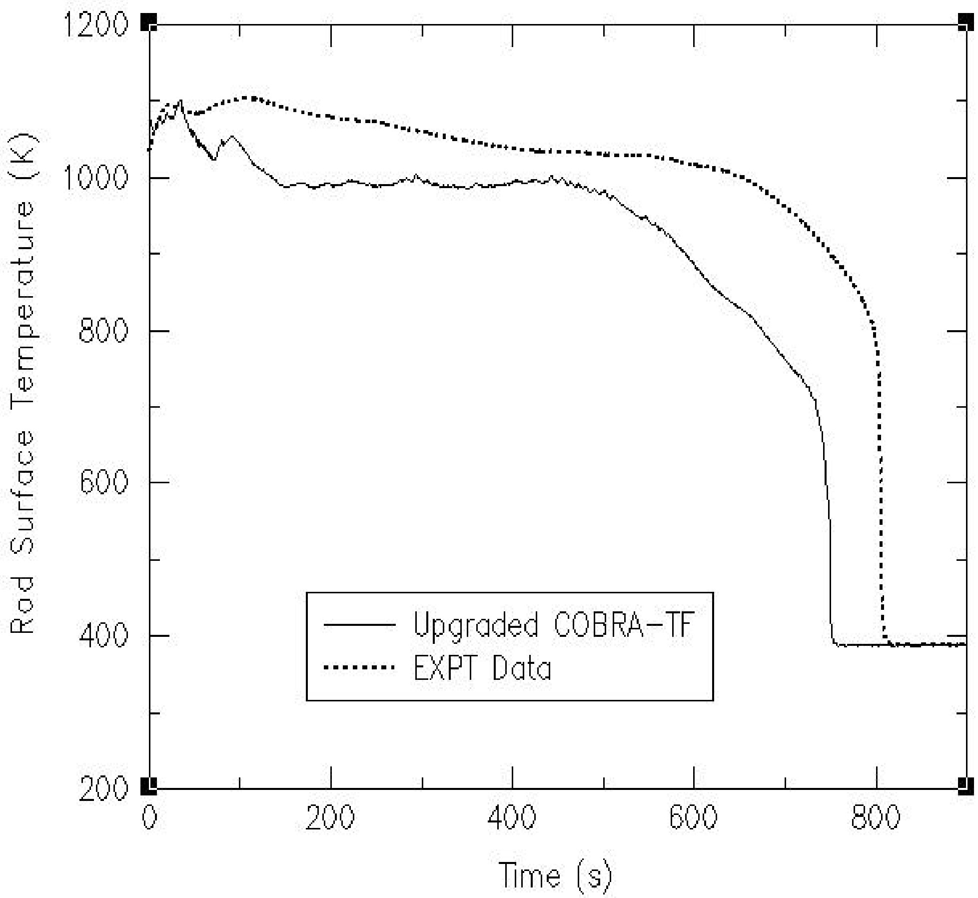
Comparison of Upgraded Code-Calculated and Experimentally Measured Quench Front Location for RBHT – Run 945 as a Function of Time



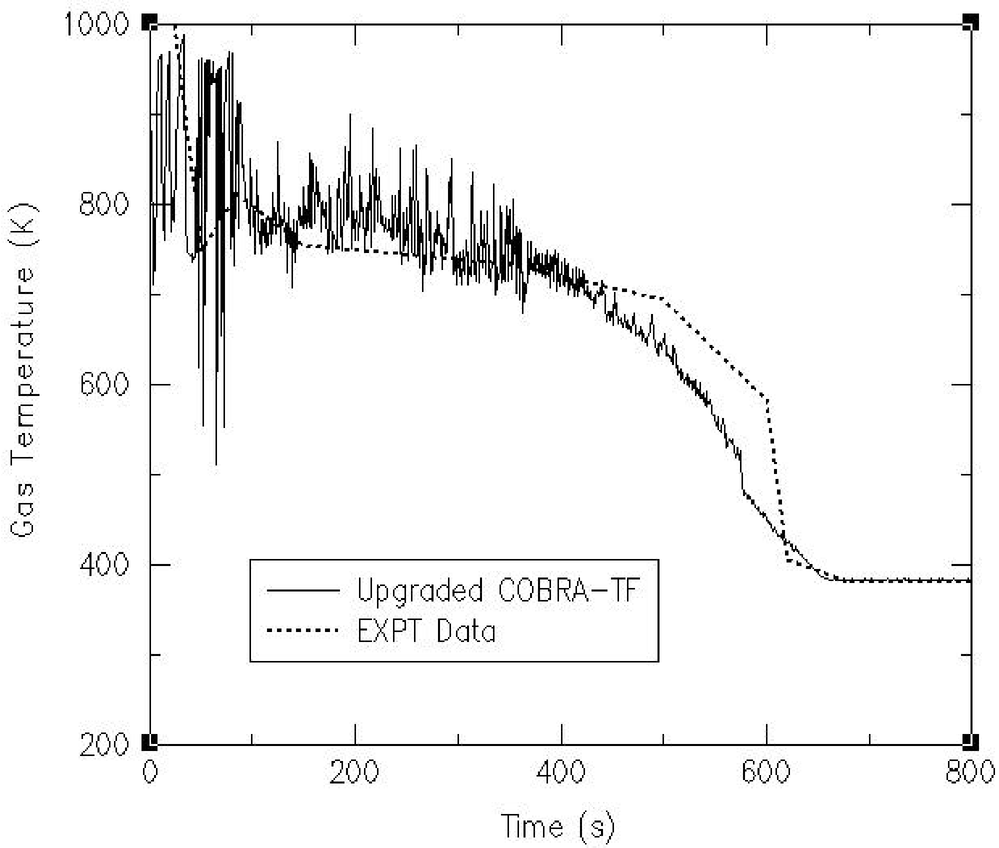
RBHT RUN 937

Upper Plenum Pressure	0.14 MPa
Initial Clad Temperature at 2.74m	1040 K
Rod Peak Power	1.3 kW/m
Cold Fill Rate	24.9 mm/sec
Injected Coolant Temperature	371 K

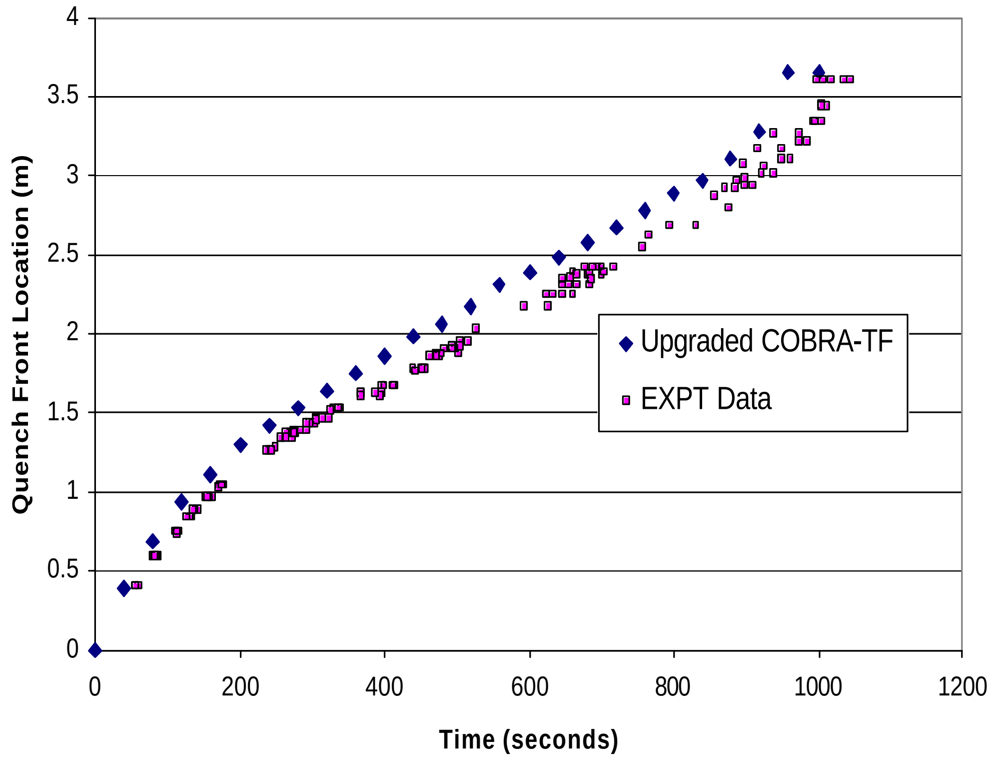
Comparison of Upgraded Code-Calculated and Experimentally Measured Clad Temperatures for RBHT – Run 937 at 2.74m Axial Elevation



Comparison of Upgraded Code-Calculated and Experimentally Measured Vapor Temperatures for RBHT – Run 937 at 2.54m Axial Elevation



Comparison of Upgraded Code-Calculated and Experimentally Measured Quench Front Location for RBHT – Run 937 as a Function of Time



Conclusions

- RBHT Program is structured to improve the reflood models in the NRC safety analysis codes.
- Improved NRC codes will aid them in audit calculations and risk informed regulations.